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Fiducialization and Calibration of Rotating Coil for Magnetic Measurements of the ERL Quadrupoles

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1. Introduction:

The Energy Recovery Linac (ERL) lattice contains quadrupoles of 30 mm radius aperture, 128 mm yoke length, and 157 mm magnetic length. It is planned to measure the field quality in these quadrupoles using rotating coils. In order to relate the measured field harmonics to the mechanical axis of the quadrupoles, it is necessary to make provisions to locate the measuring coil axis in a reference frame defined by the magnet fiducials. Furthermore, in order to obtain the best possible accuracy in the measured fields, the rotating coil must also be calibrated very precisely.

Based on the quadrupole magnet aperture and the length, the ~28 mm radius electric motor mole RE4 (containing coil #78) was selected to carry out these measurements. This mole was used extensively in the past for warm measurements of nearly 200 RHIC dipoles of 80 mm aperture and all the 20 insertion region dipoles built by BNL for the LHC. However, for the ERL quadrupole measurements, modifications had to be made in order to provide capability to survey the rotating coil. Also, the geometric parameters of the coil were calibrated again using an elaborate procedure.

This note describes the modifications made to the mole, the results of surveying the surface of the rotating coil, and the calibration procedure that was used to obtain the relevant geometric parameters.

2. Mole modifications to facilitate survey:

The mole RE4 was disassembled and 16 survey fiducials were marked on the surface of the coil form (coil #78). These fiducials were in the form of a cross made using light scribe marks, and were placed at four axial positions along the length of the coil. Four such fiducials were marked at each of the four axial positions, distributed evenly every 90 degrees along the circumference. By optically surveying these fiducials, the cylindrical coil form surface, and its geometric axis, can be determined. For the purpose of magnetic measurements, it is necessary to know the rotation axis, rather than the geometric axis of the coil. The coil is rotated by precision machined shaft, which is attached to the coil form. It can, therefore, be assumed that the rotation axis is the same as the geometric axis without making appreciable error.

The positions of the 16 fiducials on the coil were obtained by optical survey. In order to make the fiducials visible during actual use of the mole for measurements, holes were made in the outer shell of the mole at the locations of the fiducials. The mole was then assembled back. Fig. 1 shows the coil motor end of the completed mole installed in a prototype ERL quadrupole. Two of the holes in the shell showing the survey fiducials are also visible. The inset shows one of the survey fiducials in more detail.

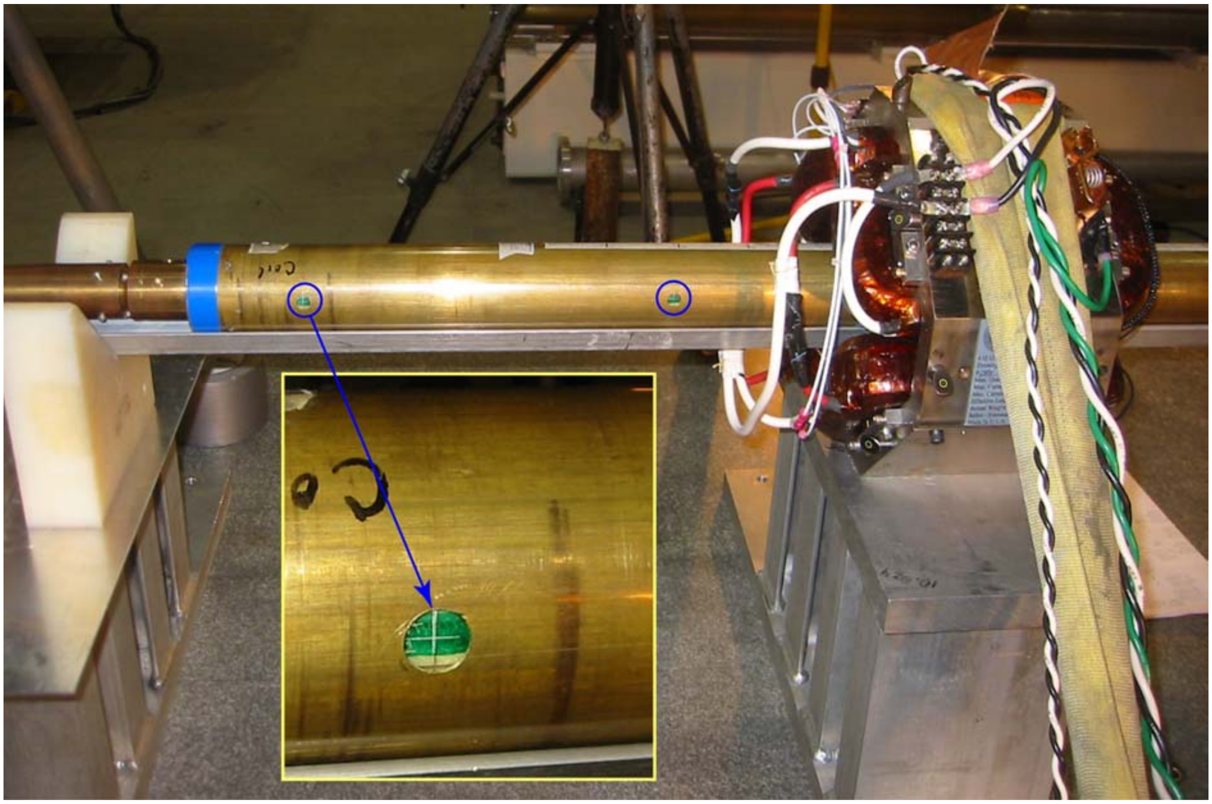

Fig. 1 Coil motor end of the mole RE4 (coil #78) showing two of the holes (marked with circles) in the shell to observe the survey fiducials on the rotating coil. The inset shows the scribe lines used to make these fiducials.

3. Analysis of the coil form survey data:

The 16 fiducials on the coil form were optically surveyed before the final assembly of the coil into the mole. Many additional points on the surface of the coil form were also surveyed. These additional points were derived from intersections of the edges of the coil winding grooves with four circles inscribed on the coil surface. There were 70 such points that were surveyed, in addition to the 16 fiducials. Thus, a total of 86 points were surveyed on the surface of the coil.

To determine the geometric axis of the coil, a cylindrical surface was fitted to the points on the coil form. Using all the 86 points, the fitted radius was found to be 27.9395 mm. Fig. 2 shows the residual errors for each point, defined as the radial distance from the fitted surface. The first 16 points are the scribe marks and the remaining 70 are the additional points that were surveyed. The errors for most points are within ±50 μm, but are as much as 150 μm for some points. It should be noted that the edges of the grooves may not be very well defined, and thus may be subject to larger uncertainties. If only the 16 scribe marks are used for fitting, then the errors for those points alone is within ±50 μm. The fitted radius in this case is 27.9402 mm, and differs by only 0.7 μm from the case where all 86 points are used. It is also noteworthy that the fitted radii almost perfectly match the design value of 27.940 mm. The axes of the two fitted cylinders differ by ~38 μrad. The geometric centers of the coil obtained from the two fits are consistent within ~25 μm.

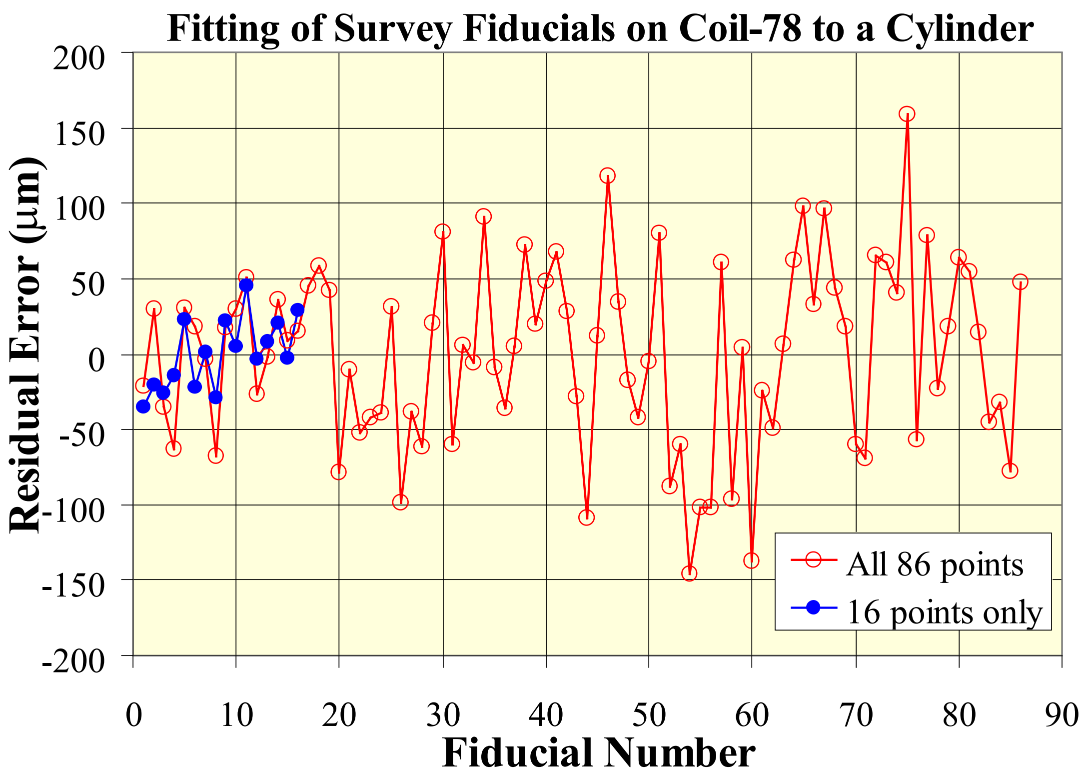

Fig. 2 Distances of the survey data points on coil #78 from the fitted cylindrical surface. The open symbols are the errors when all the 86 points are used in the fitting. The filled symbols are the errors when only the 16 scribe marks are used.

4. Calibration of the coil parameters:

Coil #78 has five windings – two dipole buck windings (DB1 and DB2), one winding sensitive to all harmonics, referred to as simply the "Tangential" winding (T3), and two quadrupole buck windings (QB4 and QB5). These windings are characterized by their geometric parameters, which include the length, the number of turns, the winding radius, the angular position of the winding, and the opening angle. In addition, it is important to consider one more parameter, which is the radius mismatch (±ε) between the two grooves of the T3 winding. Such a radius mismatch causes a tilt of the plane of the winding and adds a radial component to the otherwise tangential winding. This produces a harmonic dependent error in the measurement of the field angle [1].

The length of all windings in coil #78 is approximately 1 m. Typical construction errors are of the order of 50 μm. Thus, the length is already known to a precision of ~50 ppm. On the other hand, a similar error on the radius (~27 mm) would amount to ~0.4% error in the measurement of the quadrupole transfer function. So, it is essential to calibrate the radii and other angular parameters precisely using reference fields.

We have used a combination of a known dipole field (calibrated against NMR), an unknown sextupole field and an unknown quadrupole field to obtain all the relevant parameters of the coil. The procedure followed is described in the following sections, and is similar to that described in [1]. The relative angular positions of various windings are also accurately determined using these fields. The absolute angular positions of the windings are then determined under the assumption that the dipole field in the iron dominated reference magnet is strictly vertical. Any systematic errors in the determination of the field angle as a result of this assumption, or more importantly, as a result of subsequent drift of the gravity sensor system, can be corrected in the actual measurements by doing two measurements – one with the normal orientation of the mole, and another after turning the mole by 180 degrees about a vertical axis. Only the calibration of the radii will be covered in detail in this report, with only a brief description of the angular position calibration.

4.1 Calibration in a dipole field:

Let N_i, R_i, L_i denote the number of turns, radius and length of the i-th winding, where i=1 to 5 correspond to the DB1, DB2, Tangential, QB4 and QB5 windings respectively. Also, let Δ be the opening angle of the tangential winding. The opening angle of the dipole windings can be safely assumed to be 180 degrees, without causing appreciable error. If the coil rotates with an angular velocity ω in an axially uniform dipole field of strength B_1, then the amplitudes of the dipole term in the voltage signals of the DB1, DB2 and the tangential windings are given by:

$$V_1(1) = 2N_1 L_1 R_1 \omega B_1 \qquad \text{(DB1)} \tag{1}$$

$$V_2(1) = 2N_2 L_2 R_2 \omega B_1 \qquad \text{(DB2)} \tag{2}$$

$$V_3(1) = 2N_3 L_3 R_3 \omega B_1 \sin\left(\frac{\Delta}{2}\right) \qquad \text{(Tangential)} \tag{3}$$

In Eqs.(1)-(3), the subscript in the voltage denotes winding number and the argument in parentheses denotes the harmonic number (1=Dipole) in the Fourier decomposition of the signal. The number of turns $N_1 = N_2$ =3, and N_3 = 30 are known quantities. Similarly, the lengths $L_1 = L_2$ = 0.999998 m and L_3 = 1.000150 m are assumed to be known from the design. The angular velocity, ω, is determined from the rotation period (~3.5 s), which is measured using a 10 kHz counter. If the field strength is known, then the radii R_1 and R_2 of the DB1 and DB2 windings can be obtained from Eqs.(1) and (2).

In principle, the dipole field strength can be measured using a NMR probe. However, the mole RE4 contains electric motors in the ends which can not be placed in very strong magnetic fields. To circumvent this problem, another mole (RA2, coil #69) containing air driven motors was first calibrated in a reference dipole magnet against NMR at a higher field of 1.373 T. Mole RA2 was then used as the standard for calibrating mole RE4 at a much lower field of 0.027 T. The DB1 and DB2 windings are thus completely characterized in the dipole field. Based on three separate runs (Runs Coil78.013, Coil78.015 and Coil78.016), the DB1 and DB2 radii were determined to be R_1 = 27.4165 mm and R_2 = 27.4122 mm, with a standard deviation of ~0.3 μm (~10 ppm).

For the tangential winding, there are two unknowns, R_3 and Δ. So, we need one more equation to determine both of these parameters. Such an equation can be obtained by taking data in a sextupole field.

The quadrupole buck windings are insensitive to dipole field. So, no calibration data for these windings can be obtained in a dipole field.

4.2 Calibration in a sextupole field:

If the coil is rotated in axially uniform sextupole field, the amplitudes of the sextupole terms in the Fourier analysis of the signals of the DB1, DB2 and the Tangential windings are given by:

$$V_1(3) = 2N_1L_1R_1\left(\frac{R_1}{R_{ref}}\right)^2 \omega B_3 \qquad \text{(DB1)} \tag{4}$$

$$V_2(3) = 2N_2L_2R_2\left(\frac{R_2}{R_{ref}}\right)^2 \omega B_3 \qquad \text{(DB2)} \tag{5}$$

$$V_3(3) = 2N_3L_3R_3\left(\frac{R_3}{R_{ref}}\right)^2 \omega B_3 \sin\left(\frac{3\Delta}{2}\right) \qquad \text{(Tangential)} \tag{6}$$

where B_3 is the strength of the sextupole field at a reference radius of R_{ref}. In practice, the RHIC spare sextupole (SRE269) that was used is shorter than the measuring coil length. The above equations must be modified in this case to:

$$V_1(3) = 2N_1R_1\left(\frac{R_1}{R_{ref}}\right)^2 \omega\left(B_3L\right) \qquad \text{(DB1)} \tag{7}$$

$$V_2(3) = 2N_2R_2\left(\frac{R_2}{R_{ref}}\right)^2 \omega\left(B_3L\right) \qquad \text{(DB2)} \tag{8}$$

$$V_3(3) = 2N_3R_3\left(\frac{R_3}{R_{ref}}\right)^2 \sin\left(\frac{3\Delta}{2}\right)\omega\left(B_3L\right) \qquad \text{(Tangential)} \tag{9}$$

where (B_3L) is the integrated sextupole field at a reference radius of R_{ref}. The quantity (ωB_3L) can be eliminated from Eqs.(7) and (9) to obtain:

$$\left(\frac{R_3}{R_1}\right)^3 \sin\left(\frac{3\Delta}{2}\right) = \frac{V_3(3)}{V_1(3)}\cdot\frac{N_1}{N_3} = k_3, \text{ say} \tag{10}$$

Similarly, from Eqs.(1) and (3) in a dipole field,

$$\left(\frac{R_3}{R_1}\right)\sin\left(\frac{\Delta}{2}\right) = \frac{V_3(1)}{V_1(1)}\cdot\frac{N_1}{N_3}\cdot\frac{L_1}{L_3} = k_1, \text{ say} \tag{11}$$

Solving Eqs.(10) and (11), we get:

$$\left(\frac{R_3}{R_1}\right) = \left(\frac{k_3 + 4k_1^{\,3}}{3k_1}\right)^{1/2} \tag{12}$$

$$\Delta = 2\tan^{-1}\left(\frac{3k_1^{\,3}}{k_3 + k_1^{\,3}}\right)^{1/2} \tag{13}$$

The parameters R_3 and Δ can be easily determined from Eqs.(12) and (13), since the radius R_1 is already determined in a known dipole field. The tangential winding can thus be characterized completely without having to know the rotation speed or the strength of the sextupole field. It should be noted that one could also use the DB2 signals $V_2(3)$ and $V_2(1)$ to obtain the radius R_3 in terms of the DB2 radius. This provides an independent calibration, which may be used for an estimate of the calibration accuracy. In the case of coil #78, calibration using DB1 radius gives R_3 = 27.3253 mm and Δ = 15.020 deg. If the DB2 radius is used as a reference instead, we get R_3 = 27.3081 mm and Δ = 15.030 deg. It should be noted that although the two radii differ by about 17 μm, and the opening angle differs by 0.010 deg., the two errors are in the opposite directions, and mostly cancel each other. This is in fact expected since both DB1 and DB2 are already matched in a dipole field, and calibration using either of the two should produce the same sensitivity of the T3 winding for the dipole field. Thus, the effective calibration difference is only ~3 ppm for the dipole term, ~8 ppm for the quadrupole term, and ~26 ppm for the sextupole term. The DB1, DB2 and the tangential windings are thus well characterized using a combination of data taken in the dipole and the sextupole fields.

4.3 Calibration in a quadrupole field:

If the coil is rotated in an axially uniform quadrupole field, the amplitudes of the quadrupole terms in the signals from the quadrupole buck windings QB4 and QB5, and the tangential winding T3, are given by:

$$V_4(2) = 4N_4 L_4 R_4 \left(\frac{R_4}{R_{ref}} \right) \omega B_2 \qquad \text{(QB4)} \tag{14}$$

$$V_5(2) = 4N_5 L_5 R_5 \left(\frac{R_5}{R_{ref}} \right) \omega B_2 \qquad \text{(QB5)} \tag{15}$$

$$V_3(2) = 2N_3 L_3 R_3 \left(\frac{R_3}{R_{ref}} \right) \omega B_2 \sin\Delta \qquad \text{(Tangential)} \tag{16}$$

where B_2 is the strength of the quadrupole field at a reference radius of R_{ref}. The number of turns, $N_4 = N_5 = 3$, and the lengths $L_4 = L_5$ = 0.999998 m are assumed to be known quantities. Eliminating (ωB_2) from the above equations, we get:

$$\left(\frac{R_4}{R_3} \right) = \left[\frac{1}{2} \cdot \frac{V_4(2)}{V_3(2)} \cdot \frac{N_3}{N_4} \cdot \frac{L_3}{L_4} \sin\Delta \right]^{1/2} \tag{17}$$

$$\left(\frac{R_5}{R_3} \right) = \left[\frac{1}{2} \cdot \frac{V_5(2)}{V_3(2)} \cdot \frac{N_3}{N_5} \cdot \frac{L_3}{L_5} \sin\Delta \right]^{1/2} \tag{18}$$

Eqs.(17) and (18) gives the radii of the quadrupole windings QB4 and QB5 in terms of the already determined parameters of the tangential winding, without having to know the actual quadrupole field strength or the rotation speed. The radii of the quadrupole windings QB4 and QB5 in coil #78 were thus determined to be 27.4109 mm and 27.4248 mm respectively. Radii of all the windings and the opening angle of the Tangential winding are thus calibrated.

4.4 Further adjustments to the winding radii:

Since we had used Mole RA2 (coil #69) as a reference for calibration in the dipole field, the complete calibration procedure in the sextupole and the quadrupole fields, described above, was also followed for this coil. After the calibrations, the absolute values of the quadrupole field measured simultaneously with the two coils differed by ~0.06%. This represents the limit of accuracy achievable with this calibration procedure. This discrepancy mainly results due to the fact that the as-built coils have small axial variations in the construction errors (see Sec. 5), whereas the calibration algorithm assumes perfect axial uniformity. Since it was difficult to say which of the two coils produced results closer to the actual value, it was decided to adjust the calibrations of both the coils such as to produce a value of the quadrupole field strength equal to the average value obtained before this adjustment, but at the same time not affecting the calibration for dipole fields. In other words, the parameters R_3 and Δ were adjusted such that the quantity $\left(R_3^2 \sin\Delta\right)$, which governs the quadrupole field sensitivity, changed by ±0.03% for the two coils, but the quantity $\left[R_3 \sin(\Delta/2)\right]$, which governs the dipole field sensitivity, remained unchanged. After this adjustment, the parameters for the tangential winding became $R_3 = 27.3178$ mm and $\Delta = 15.024$ deg. Accordingly, the radii of the QB4 and QB5 windings also changed to 27.4071 mm and 27.4210 mm respectively (a change of 3.8 μm from a "blind" calibration), as per Eqs.(17)-(18).

4.5 Calibration of winding angular positions:

The time $t = 0$ in any revolution is defined by an index pulse from the angular encoder, which triggers the start of data acquisition. The phases of the signals from various windings are related to the angular positions of the windings at $t = 0$. The angular positions of the DB1 and DB2 windings are easily determined in the reference dipole field by making the assumption that the dipole field is strictly vertical. Even if this assumption were not strictly true, it will only cause a systematic offset in the angular positions of all the windings, which can be corrected later on (see also Sec. 5). The relative angular positions of various windings are more important, and these can be measured to a typical accuracy of ~±0.002 deg. (±35 μrad).

Determining the angular position of the Tangential winding (T3) is not so straightforward. This is because even a minute tilt of the plane of the winding from the tangential plane introduces an out of phase signal component, causing significant errors in the phase. Such a tilt results in a harmonic dependent error in the phase of the signal [1]. The tilt in the plane of the as-built tangential winding can be determined by comparing the phases of the signals from the T3 and the DB1 winding, say, in a dipole and a sextupole field. For coil #78, this tilt was measured to be ±10 μm over the width of the winding (or ~2.7 mrad). Having determined the tilt, the phase of the tangential signal can be corrected in a field of any multipolarity. The corrected T3 signal phase is then used as a reference in a quadrupole field to measure the angular positions of the quadrupole buck windings QB4 and QB5. In this way, the *relative* angular positions of all the five windings are very accurately determined.

The final parameters of various windings in coil #78 (mole RE4) are given in Table I.

Table I: Parameters of various windings in coil #78 (mole RE4)

Parameter	DB1	DB2	Tangential	QB4	QB5
No. of Turns	3	3	30	3	3
Length (m)	0.999998	0.999998	1.000150	0.999998	0.999998
Radius (mm) from magnetic calibrations	27.4165	27.4122	27.3178	27.4071	27.4210
Radius (mm) from groove depth measurements	27.4108	27.4151	27.3710	27.4087	27.4066
Opening Angle (deg.)	180.0	180.0	15.024	90.0	90.0
Angular Position (deg.) from magnetic calibrations	308.017	46.432	357.171	152.407	22.060
Angular Position (deg.) Design Value*	307.957	46.477	357.217	152.377	22.057
Tilt (mm)	—	—	±0.0096	—	—

* The design values of absolute angular positions are calculated using a rotation of the coil that gives the best fit with the calibration values.

4.6 Magnetic calibration results compared to the expected values:

Before laying various windings into the coil form, the depth of each groove is carefully measured at several locations along the length. The radii of various windings can be estimated from the known coil form radius, the measured groove depths, the wire size and number of layers. These estimated values of radii are also given in Table I for comparison with the radii derived from magnetic calibration. It is seen that the agreement between the mechanical and magnetic calibration is generally within a few microns, except for QB5 which differs by 14.4 μm, and the T3, which differs by ~53 μm. It should be noted that the T3 winding has five layers of 150 μm diameter wire, which makes it somewhat difficult to estimate the effective radius from the groove depths. All the other windings have only a single layer of wire, and the wire position is better defined mechanically.

The angular positions of the as-built windings are more difficult to measure mechanically. In this case, we can compare the results of calibration with the design values. For an absolute comparison, we have rotated the coil as a whole such that the chi-square defined as the sum of the squares of the differences between the design and the calibration values is minimized. These design values are also given in Table I. It can be seen that the agreement between the design and the calibration values is generally within ~±0.050 degree, or ~±1 mrad. This corresponds to a groove location error of ~±25 μm. It should be noted that the angular positions are calibrated with a typical uncertainty of ±0.002 degree, which is significantly better than the typical construction accuracy.

5. Test of axial uniformity:

The calibration procedure described above assumes that various winding parameters are constant along the length of the coil. In practice, there are small construction errors in the radius and angular positions of the grooves. These errors are not the same throughout the length of the coil. Accordingly, the calibration provides only effective values of the parameters, when the field is axially uniform throughout the 1 m length of the coil. In this case, the measurement of absolute field strength is expected to be within approximately ±0.01% and ±0.05% for dipole and quadrupole fields respectively.

In the case of measurements of the ERL quadrupoles, the magnet core length is only 0.128 m and the magnetic length is only 0.157 m. These measurements are therefore sensitive only to the coil parameters in a localized region of the coil. Even a 25 μm deviation of the local radius from the average would result in ~0.2% error in the absolute value of the quadrupole field. To circumvent this difficulty, it was decided to study the axial variation of the sensitivity of the QB1, QB2 and T3 windings to the quadrupole field. This was done by carrying out measurements of the quadrupole field in the prototype ERL quadrupole magnet with the measuring coil at several axial positions. Each measurement maps out the effective radii and angular positions in a different ~0.2 m long section of the coil.

Fig. 3 shows the variation of the integral transfer functions measured by the QB4, QB5 and T3 windings as a function of the axial position of the measuring coil. A zero axial offset corresponds to the position where the axial center of the measuring coil is at the axial center of the magnet core. This is the nominal position that would be used for all measurements. In order to clearly show the magnitude of the variation, the deviation of each measurement from the average of all readings is plotted instead of the absolute values. The results from the QB4 and the QB5 windings track each other, which indicate that the variation is more likely to be caused by local errors in the coil form radius, rather than errors in machining the grooves. It is possible that the drop at the extreme positions (±300 mm) may at least partially be due to

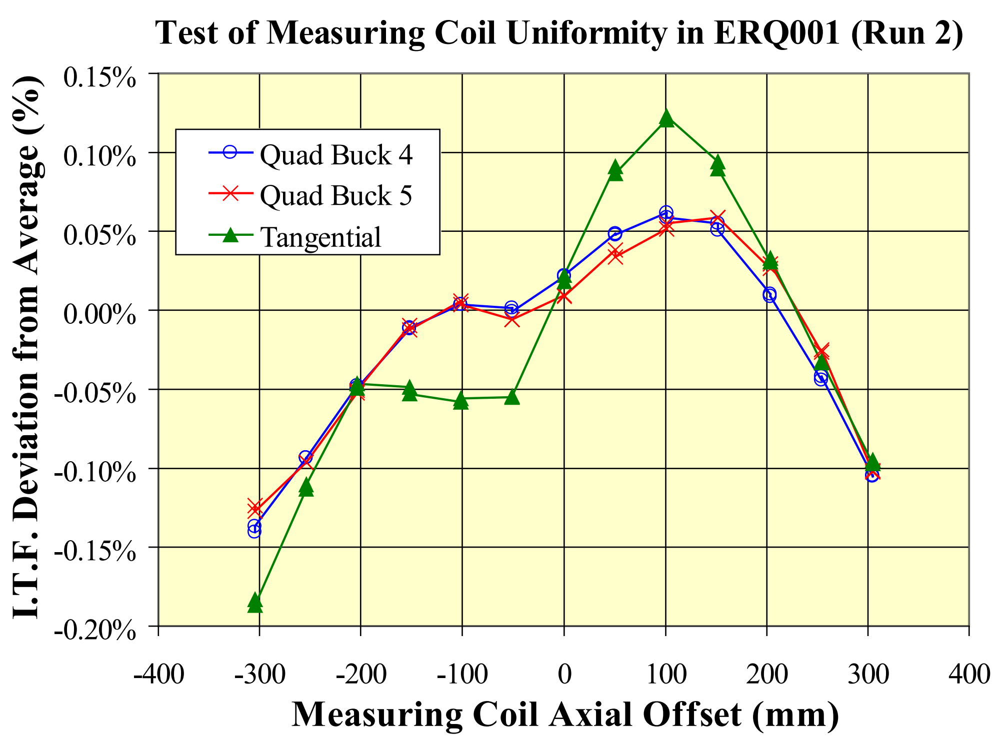

Fig. 3 Variation of integral transfer function measured in the prototype ERL quadrupole ERQ001 as a function of the axial position of the 1 m long measuring coil.

missing some of the fringe fields. Neglecting the extreme positions, the variation of integral transfer function from the QB4 and QB5 windings is less than ±0.1%, corresponding to radius errors of less than ~14 μm. The tangential winding (T3) shows slightly more variation than the QB4 and QB5 windings. This is because the signal from this winding is sensitive not only to the radius errors, but also to the angular positions of the two grooves, which affect the opening angle.

A remarkable feature that is evident from Fig. 3 is that the integral transfer function measured with zero offset (the nominal coil position) is almost the same as the average value. In other words, the absolute values measured with the nominal coil position are likely to be quite accurate, and do not need any further renormalization.

Fig. 4 shows a plot of the variation of the quadrupole field angle measured by the QB4, QB5 and the T3 windings as a function of the axial position of the 1 m long measuring coil. Once again, the deviations from the average value are plotted instead of the absolute values. These variations are caused by errors in the angular positions of the winding grooves. Typical errors are ~±0.5 mrad, which correspond to an error of ~14 μm in the groove position along the circumference. The azimuthal position errors are thus of the same order as the radius errors.

The field angle measured by the QB4, QB5 and T3 windings have errors of 0.03 mrad, 0.24 mrad and 0.30 mrad respectively when the coil is centered in the magnet. The data analysis software reports an average value from QB4 and QB5, which would have an error of ~0.13 mrad. Since the absolute field angles measured by moles are known to drift with time for reasons not yet fully understood, the standard practice for precise field angle measurements is to measure the magnet twice – once with the mole placed normally in the

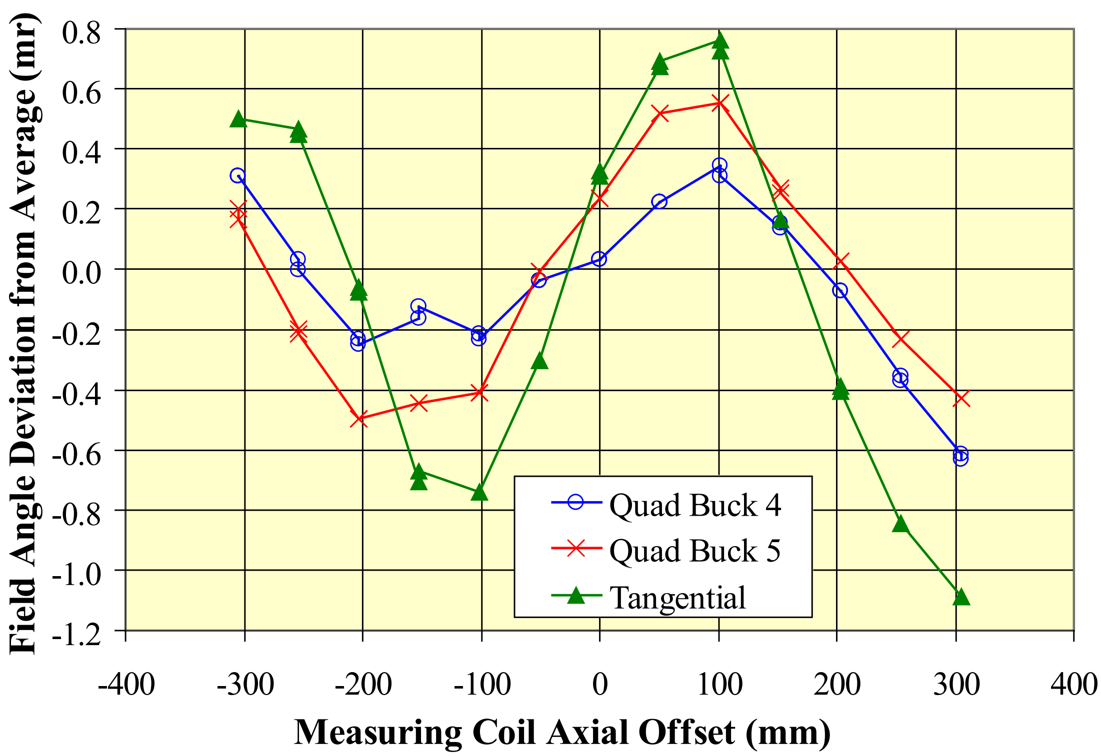

Fig. 4 Variation of quadrupole field angle measured in the prototype ERL quadrupole ERQ001 as a function of the axial position of the 1 m long measuring coil.

magnet (with the coil drive motor on the lead end side of the magnet, say), and then again with the mole turned 180 degrees around a vertical axis (with the coil drive motor on the non-lead end side). Any true deviation of the field axis from the vertical direction would change sign in the two measurements, but any systematic errors in the measurement of the field angle would remain the same. By comparing the field angles in the two measurements, it is possible to derive the systematic error, as well as the true field angle. Such measurements carried out subsequently in the prototype ERL quadrupole (ERQ001, runs 49 and 52) showed that this systematic error in the angle calibration is 0.16 mr, which is in good agreement with the error of 0.13 mr estimated from Fig. 4. This agreement also validates the assumption made earlier that the field in the calibration dipole magnet is strictly vertical.

6. Summary and conclusions:

The electric motor mole RE4 (coil-78) has been modified to place survey fiducials on the rotating coil form. These survey fiducials will help in locating the axis of the measuring coil during the production measurements of the ERL quadrupoles. It is estimated that the measuring coil center can be determined with an uncertainty of less than 25 μm using these fiducials. The geometric parameters of various windings of the coil have been determined with the best possible precision using an elaborate procedure of measurements in a dipole, a sextupole and a quadrupole field. The absolute calibration is matched to another mole RA2 (coil-69), which in turn was calibrated to match NMR readings in a dipole field. The absolute error in the quadrupole field strength measurement is estimated to be less than ±0.05%. This corresponds to an uncertainty of less than ±7 μm in the winding radius. The calibration parameters were also shown to be in reasonable agreement with the expected parameters. For the purpose of measuring the short length ERL quadrupoles, the axial variation of the sensitivity of various windings to the quadrupole field was studied in a prototype magnet. Based on the observed axial variation, the typical construction errors were shown to be ~±14 μm. It was shown that the quadrupole field strengths measured with the mole RE4 centered in the ERL quadrupole do not need any further renormalization to account for axial variations of the construction errors.

7. Acknowledgements:

We thank Daniel Sullivan for making the required modifications to the mole, and Andrew Sauerwald and John Cintorino for their support in carrying out the calibration and field measurements. We also thank Douglas Gordon and Ed Ulrich for surveying the mole coil form, and Frank Karl for providing the survey data.

8. References:

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